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Flexible Fiberoptic Endoscopy and Laser Surgery in Obliterated Cochleas: Human Temporal Bone Studies

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***Background and Objective*: The use of conventional drilling procedures in cochlear implant surgery of ossified cochleae poses special risks to the facial nerve and the carotid artery. This study evaluated the alternate use of flexible fiberoptic endoscopy and mid-infrared laser surgery for recanalization of partially and artificially obliterated cochleae in freshly dissected human cadavers.**

***Study Design/Materials and Methods*: A pulsed Holmium:YAG-laser (λ = 2120 nm) was used in the free-running mode (1180 mJ, 250 μs pulse, 5 Hz). A 660 μm optic quartz fiber was positioned in the center of the round window niche and slowly—endoscopically guided—advanced in contact shooting over 1.5 cm, creating by vaporization and photoablation a passage through the artificial bony occlusion in the basal segment of the cochlea.**

***Results*: In all experiments, laser application (110–130 pulses) resulted in complete recanalization of the bony occlusions without damaging surrounding structures. The microendoscopy proved capable of guiding the laser fiber through the curved segment of the basal turn allowing identification of normal bone, bone cement, and laser-treated bone cement.**

***Conclusion*: If partial ossification of the basal turn is present, this technique could give access to place analog as well as digital implants deep within the cochlea.**

Key words: cochlea, endoscopy, cochlear implant, Holmium:YAG-laser

INTRODUCTION

Cochlear scala tympani implantation is chosen by a majority of implant surgeons because of proximity to the middle ear, accessibility, and the belief that intracochlear systems are superior to extracochlear ones [1]. Partial or complete ossification of the cochlear scalae is a common occurrence in patients with nonspecific congenital deafness and profound deafness resulting from meningitis, temporal bone fracture, otosclerosis, autoimmune diseases, Ménière's disease, or ototoxicity [2,3]. The scala tympani, particularly in the basal turn region, is the segment of the cochlea most commonly affected by fibrosis and new bone formation [4]. Many attempts have been made to overcome the difficulties involved in placing intracochlear devices in case of scala tympani obliteration. Good results with implantation following drilling out of the ossified part of the scala tympani were reported by Balkany et al. [2].

In conjunction with external canal obliteration, Ganz et al. [1] have described an elaborate new technique that involves creating a channel around the modiolus by drilling out the cochlea and middle ear. Most implant surgeons, however, select either an extracochlear implant device [5] or short intracochlear ones, given the increased

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risks, especially to the facial nerve and carotid artery, associated with extensive conventional drilling procedures. We attempted to elaborate an operating method based on optical drilling with a pulsed high-energy, solid-state Holmium:YAG infrared laser. This method provides the advantage of carefully controlled bone ablation with reduced mechanical force in areas with limited surgical access.

In contrast to currently used lasers in otologic surgery, this new type of laser proved suitable for proper surgical proceedings in both micro- and macrosurgery of bone and soft tissues [6–9] due to its different mode of ablation and its advantageous water and bone absorption coefficient. The Holmium:YAG infrared laser certainly causes more thermal injury than the Erbium: YAG-laser, the most promising laser for bone ablation. It is, however, superior to other continuous-wave lasers applicable in microsurgery of the middle [10,11] and experimental surgery of the inner ear [12]. We have previously demonstrated in an in vitro study on temporal bone models [13] that the Holmium:YAG-laser may be effectively used for safe reopening of artifically obliterated human cochleas over a length of 8–10 mm. In the course of this study, however, difficulties with steering the laser fiber and advancing it through the first genu of the cochlea became apparent. In a recent study, Balkany et al. [14] found a flexible fiberoptic otologic endoscope capable of passage through the scala tympani of the cochlea in the inferior segment and of identifying normal and abnormal structures.

MATERIAL AND METHODS

Microendoscope, Laser Light Delivery System

The smallest currently available size of 90° actively steerable microendoscope (OM3-080) with a total diameter of 0.85 mm was used (Omegascopes™, Omega Fiberoptic Imaging, London, UK). The OM3 is a microendoscope consisting of ultrathin, flexible fused, silica imaging fibers and light illumination bundles and is suitable for direct and video endoscopy. The field of vision is 70° with a depth of focus from 2–20 mm. Magnification is 50 ×. A 300 W light source was utilized.

The pulsed Holmium:YAG-laser (BLM 800, Baasel Laser Tech, Starnberg, Germany) was used at a wavelength of 2,120 nm in a free-running mode (pulse duration 250–1,000 μs, repetition rate 5 Hz). The laser pulses were transmitted to the target by a 660-μm core diameter quartz fiber. A quartz fiber with an original outer diameter of 920 μm was stripped of the casing, resulting in a 660-μm core diameter and a temporary average minimum bending radius of 1 cm and a divergence angle of 20°. The top of the fiber was calibrated in mm steps. For preflexing, the tip of the fiber was passed through an unrestrictedly bendable metal canula with an outer total diameter of 0.8 mm (Dr. Koch GesmbH, Vienna, Austria). The Holmium:YAG-laser was tested at energy settings increasing from 500–2,500 mJ.

Surgical Procedure

In nine human temporal bones, the lateral wall of the middle ear was removed with the band saw, leaving the medial (labyrinthine) wall exposed. The stapes, interior-inferior lip of the round window niche, and the round window membrane were removed under a Zeiss surgical microscope. The endoscope was inserted into the cochlea under endoscopic visualization documented by SVHS videotape until the curved segment of the basal turn was visible. Then, the tip of a flexible plastic canula, which was connected to the incapsulated bone cement ready for use in the bone cement applier, was inserted 1 cm deep into the scala tympani.

During withdrawal of the canula, constant filling took place, ensuring complete obliteration of the curved and straight part of the basal turn. For this investigation, surgical Ionocem Ionocap bone cement (Ionos, Seefeld, Germany) was used. The filling in the cochleas was allowed to solidify for at least 1 hr at room temperature. Then, the quartz laser fiber was brought in contact with the center of the round window niche. The pulsed Holmium:YAG-laser was used to drill out the basal turn of the scala tympani beyond its curved segment. During ablation a gentle mechanical pressure was applied to the fiber to ensure continuous contact with the bone cement.

To avoid smoke formation and to minimize potential thermal side effects, the target area was irrigated with NaCl throughout the experiment. To prevent leaving the scala tympani at the beginning of the curved segment of the basal turn, the laser fiber was withdrawn at the 6 mm calibration point and the passageway of the laser within the bone cement endoscopically examined. After complete removal of the artificial bony occlusion, indicated by a change of photoacoustic side effect into a hollow sound and the stop of material ejection, endoscopy of the recanalized scala tympani was repeated.

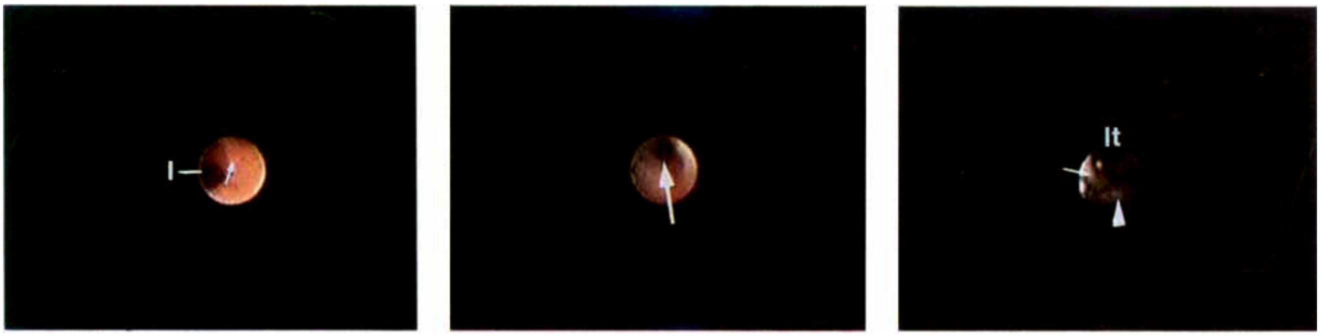

Fig. 1. Endoscopic photographs (videoprints): (**a**) of scala tympani (at 7 mm) before laser surgery; its walls appearing slightly reddish; the basilar membrane marked with arrow; lumen (l); (**b**) of recanalized straight part of the basal turn of the cochlea (at 6 mm); its walls appearing gray to black; (**c**) of laser exposure of the bony wall (arrow) with appearance of glasslike fusion of the filling material (arrowhead) at 9 mm; laser track (lt).

Histology

Histologic investigations were made on sections of the petrous part of the human temporal bones orientated vertical to the reopened straight part of the basal turn. The tip of a plastic canula was placed in the reopened basal turn to mark its position within the petrous bone. For histology, the bones were fixed in 7.5% formalin for 48 hr, dehydrated through an extended graded ethanol series, and subsequently embedded in methacrylacid-methylester. After polymerization, specimens were fixed on plexiglass microslides and a thin-section technique was used to bring each section to a thickness of 10–15 μm, orientated parallel to the modiolus. A modified trichrome Goldner surface stain was applied after erosion with 30% H_2O_2. Slides were examined under light microscopy and measured by ocular micrometry.

RESULTS

Microendoscope, Laser Light Delivery System

The flexible fiberoptic endoscope proved capable of advancing into the scala tympani beyond the first turn of the cochlea. The maximum insertion length into the cochlear ducts is determined by the length of the actively steerable fiber tip and its maximum bending angle of 90°. The endoscope provides a three-dimensional picture of the cochlea. Despite extreme reduction in size of the objects resulting in less than ideal image quality, the integrity of the walls, showing a slightly reddish colour (Fig. 1a) and of conducting structures such as the basilar membrane and the stria vascularis, can be accurately assessed.

Under the surgical microscope, laser application with simultaneous flushing appears as a pulse-by-pulse ablation of the filling material with approximately circular cratering and moderate carbonization. Advancement of the fiber in contact shooting produces a laser tunnel with smooth contours. During laser operation, the tip of the fiber emits a white to yellowish flame accompanied by a photoacoustic snapping. In all experiments laser application resulted in complete recanalization of the bony occlusions. The free-running mode produced proper tissue ablation at the energy fluence used and led to constant advancement of the fiber into the bone cement as soon as the ablation process started. An average of 110–130 pulses at a single pulse energy at the tip of the fiber of 1180 mJ were applied. In all cases the initial passage of the laser fiber through the straight part of the basal cochlea was either approximately concentric or slightly off-center, oriented toward the modiolus. With further advancement the fiber deviated from its initial location to a suboptimal plane at the lateral bony wall of the scala tympani at the inferior portion of the ascending turn.

In seven cases, this off-center position of the laser fiber did not lead to wall perforation, due to the bending properties of the fiber, and did not interfere with further recanalization. In two cases unguided advancement of the laser fiber without alternate use of the endoscope would have resulted in wall perforation in a distance of 7.5 mm from the round window membrane. Preflexing of the fiber tip by bending the tip of the metal canula was sufficient to reguide the fiber tip into the obstructing bone cement.

Endoscopy correspondingly reveals a sharply delimited laser track in the straight part of the basal turn, its walls appearing grey to black (Fig.

1b). In the curved segment, however, in a distance of 7–9 mm from the round window niche, signs of a more marked thermal injury can be detected, especially on the lateral walls, in the form of a glasslike fusion of the filling material. Laser application also leads to ablation of the lateral and/or medial bony walls, endoscopically visible as grey to whitish colouring (Fig. 1c). The endoscope permits not only clear identification of laser-treated bone and bone cement as well as of the laser track within the filling but also provides clear evidence of the patency of the scala following laser application.

Histology

Serial sections of the cochlea revealed the laser tunnel within the filling cement in the basal cochlear ducts. The laser-induced defect had clean margins. The zone of damage around the laser tunnel following Holmium:YAG-laser application in the free-running mode can be compared to the damage following Holmium:YAG laser application in the Q-switched mode, except for the zone of damage being—with 50–200 μm—considerably more extended. The endoscopic findings are confirmed by histologic examinations: the laser track laterally leaves the bone cement in the curved segment of the basal turn, ablation of the bony wall occurred (Fig. 2). In cases were the laser track was initially positioned closer to the medial wall, the defect is at times a mere 150 μm away from neural structures (Fig. 3b). The maximum depth of penetration of the laser tunnel into the basal turn is ascertained by serial sections oriented parallel to the round window niche (Fig. 3a–c). Laser-induced lesions are demonstrable in the first five sections on average. Given a section thickness of 3 mm each and taking into account the gradient of the cochlear scala, the average approximate maximum penetration depth can be assessed at 12–15 mm.

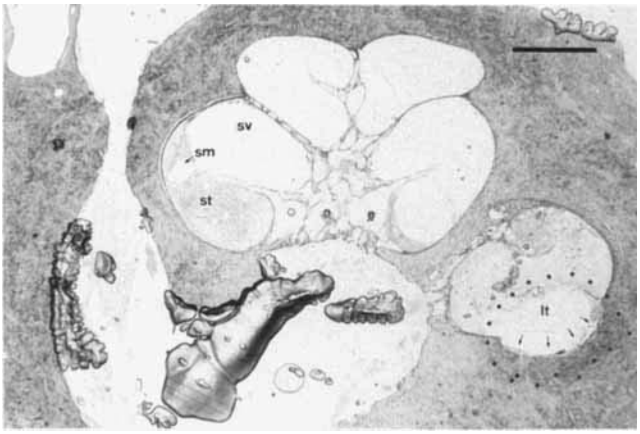

Fig. 2. Midmodiolar section of a right human temporal bone (Trichrome-Goldner, bar = 1 mm); laser track in the filling material (lt) with ablation of the lateral bony wall (arrows); laser induced damage zone marked with dots. Scala tympani (st); scala media (sm); scala vestibuli (sv).

DISCUSSION

The question whether fibrous obliteration or ossification of the cochlea is a contraindication to implant surgery comprises three problematic points, which also play a decisive role in assessing the surgical applicability of the laser.

1. Modern imaging may fail in detecting signs of ossifying labyrinthitis, especially when an intracanal fibrosis has not yet ossified. Therefore some authors consider "exploratory cochleostomy" the only definite way of determining the extent of cochlea patency [3]. The insertion length of a flexible fiberoptic otologic endoscope was limited to 10 mm due to its inherent stiffness, which resulted in damage to the spiral ligament at the ascending turn [14]. Experimental studies in electrode placement into human temporal bones showed an average distance of 12 mm from the round window membrane to the point in the scala tympani where the electrode had navigated the critical first bend and was in position to slide without further difficulties toward the full length of the scala. To bridge the distance between the point of contact with the exterior lateral wall of the scala tympani and the 12 mm point, the electrode had to bend 90°, necessitating an average bend of 15°/mm [15]. The 90° actively steerable microendoscope used by our study group fulfilled this bending requirement. As a result, a measured average insertion length into the scala tympani of 12–15 mm could be achieved without damage being inflicted on the spiral ligament. The tunnel excavated by the laser within the bone cement was clearly visible in all cases. In combination with laser surgery, the presence and extent of the bone cement in the scala tympani could be better ascertained than in a previous study using high-resolution computerized tomography [13].

2. Histologic investigations in bones with ossified cochleas revealed a substantial decrease of ganglion cells, which are generally considered susceptible to electric stimulation [16]. Insertion of electrodes over a length of 10 mm or less reduces the chance of stimulating a sufficient num-

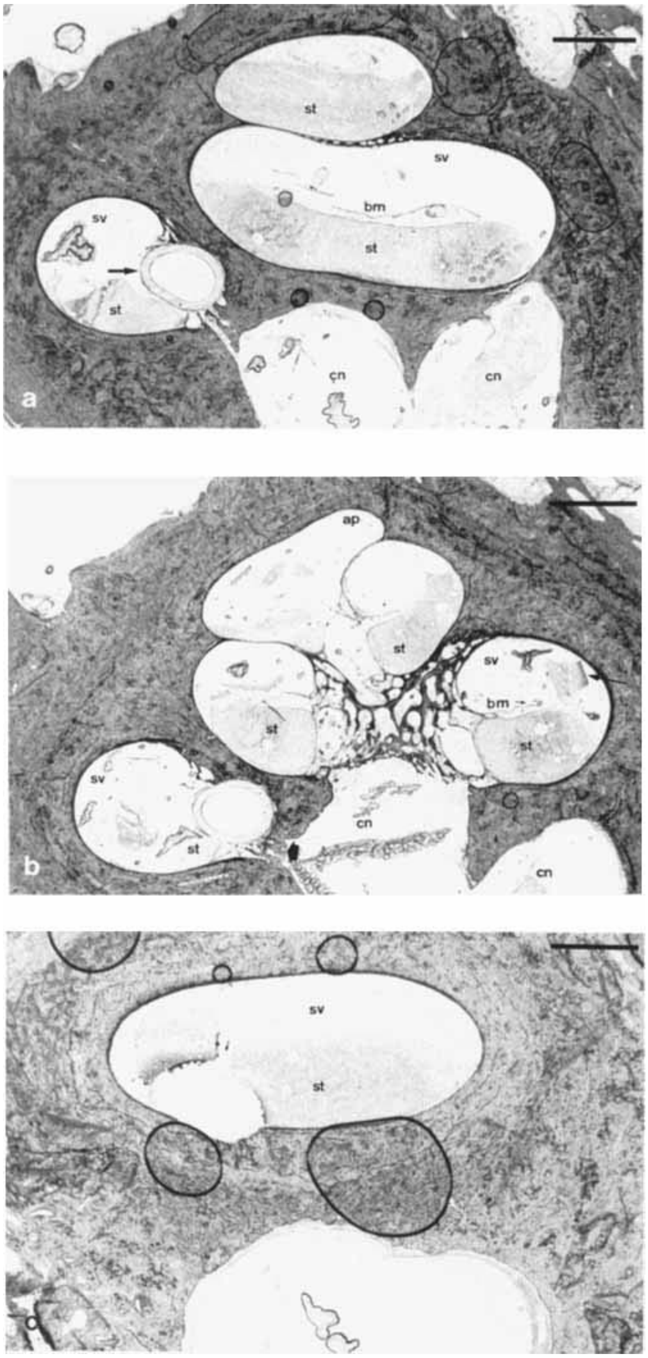

Fig. 3. Histological sections of a left human temporal bone (Trichrome-Goldner, bar = 1 mm) with laser-induced lesions visible in six sections; three sections being demonstrated. (**a**) Section close to the round window area; laser track oriented towards modiolus marked with a plastic canula (arrow); scala tympani (st) filled completely; cochlear nerve (cn); basilar membrane (bm); scala vestibuli (sv). (**b**) midmodiolar section: shortest distance of laser damage zone to cochlear nerve region (cn) 150 μm (arrowhead); basilar membrane (bm); apex (ap); laser-treated bone cement in the second turn (arrow); scala tympani (st); scala vestibuli (sv); (**c**) Section located farthest from round window, deviation of laser track (lt) to a lateral position; scala tympani (st); crack within the filling material not induced by laser but by cutting (arrows); scala vestibuli (sv).

ber of excitable ganglion cells. Whereas the zone of laser damage surrounding the laser track in the basal turn medially comes close to neural structures (Fig. 3b), it is situated in what appears to be a safe distance from the ganglion cell bodies in the center of the modiolus. Since this study was executed on material extracted from cadavers, no clear distinction between autolysis and laser-induced damage of neural structures can be made. The extent of the damaged zone, however, leads us to assume autolysis. Moreover, in temporal bone studies the upper portions of the cochlea, which remain unaffected by laser application, tend to have the highest number of unimpaired neurons [17].

3. For the use of multichannel cochlea implant systems, a modified surgical approach is needed to overcome difficulties in placement of intracochlear electrodes. Implantation of partially ossified cochleas with long multichannel electrodes is commonly achieved by way of the scala tympani following removal of the bony obstruction. This procedure works well to a maximum distance of 8 mm (4.5 mm on average) from the round window membrane [3]. Conventional drilling procedures, however, bear an increased risk to the wall of the carotid artery, located at 750 μm from the basal turn at the level of the round window niche [15].

The applicability of the Holmium:YAG-laser type in inner ear surgery for safe reopening of completely obliterated cochleas over a length of 10 mm led us to explore an improved method. In combination with flexible fiberoptic endoscopy, the fiber could be guided to the middle turn of the cochlea, which allows placement of analogue as well as digital implant devices within the cochlea. The difficulty of partial ossification of the basal turn, even in case of an obliteration located in the curved segment of the first turn, poses no particular problem.

Our attempt at immediate "microendoscopically controlled laser surgery" within the cochlea, using the same size of microendoscope, this time, however, with a working channel of 0.45 mm instead of an actively steerable fiber tip and a 400-μm core diameter laser fiber failed. The combination of the two devices lead to an unexpected stiffness of the resulting system. In addition, every single laser shot caused soiling of the optic whether irrigation was used or not, which renders proper surgical proceedings impossible. Similar to the mechanism of bone ablation proposed by Nelson et al. using the Erbium:YAG-laser [18], it is hypothetically assumed that Holmium:YAG-laser light is effectively absorbed in tissue by water,

causing fast heating of working surfaces with small volumes. The resulting high internal pressure may lead to material removal in the form of a microexplosion with parts of the cellular elements being ejected as microscopic particles. Even use of the Erbium:YAG laser, showing the most favorable damage profile of all infrared lasers, has resulted in increasing zones of thermal injury in ionomeric cement at increasing energy levels [19]. The Holmium:YAG-laser produces more thermal damage in the form of tissue necrosis and carbonization than the Erbium:YAG-laser. Heat may have an additional effect in ionomeric cement, i.e., melting.

On the basis of studies with polymethylmetacrylate [19], molten filling material as identified by endoscopic examination (Fig. 1c) can therefore be explained by the specific chemical and physical characteristics of ionomeric cement. Unsatisfactory cooling of the target zone may constitute an additional factor. It results from the ejection of cooling liquid caused by photoacoustic action, the effects of which only become apparent at increased penetration depths. The maximum temperature increase following exposure to the holmium laser was moderate in the human footplate [7] as well as in maxillary bones of live animals [20]. During 10 sec of laser exposure (820 mJ/3 Hz), temperature measured directly in the maxillary bone at a distance of 800 μm from the laser target zone increased from 32°C to 66°C, correlating with the physical effects of photoablation.

Although little experimentation has been done to determine thermal conductivity, specific heat, heat capacity, and heat of fusion for ionomeric cements, those values reported to date have been significantly lower than those for cortical and cancellous bone [19]. The histological character of tissue interaction with the Holmium:YAG-laser in the power setting as described in the free-running mode is similar to that of the Holmium:YAG-lasers in the Q-switched mode, assessed in former studies of our study group [7,20]. The damage induced in the free-running mode being markedly more pronounced, it is nevertheless not strongly associated with potentially damaging thermal effects. The presence of plasma illumination during hard tissue processing with high fluences suggests that thermal ionization or photoablation occurred. However, light microscopic changes following laser surgery are not specific to photoablation but are in part also consistent with a simple thermal damage profile of laser energy with very high water absorption. The present results of our study group, although encouraging, are only preliminary. Further improvements might be achieved if ENT specialists and industrial companies actively cooperated in investigating the effects of variables such as configuration of the tip of the microendoscope, working channel with an overall diameter capable of accommodating flushing, suction and laser fiber within the endoscope, and laser light delivery systems.

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